



Modelling road transport emissions in Germany – Current day situation and scenarios for 2040

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ARTICLE INFO

Keywords:

Future scenarios
Emission modeling
Road transport
Traffic modeling

ABSTRACT

In the German project Traffic Development and the Environment an advanced model chain was built up that includes traffic models, fleet composition developments, new driving technologies, and emission factors in order to produce spatio-temporal emission distributions for use in atmospheric chemistry transport models. This novel model chain was first used to calculate current day traffic emissions in Germany and then to develop consistent future scenarios for 2040. In all scenarios, NO_x emissions from traffic decrease by approximately 80% while PM emissions show a lower reduction. The scenarios *Free Play*, which is based on a free market economics logic, and *Regulated Shift*, which considers stricter environmental regulations, represent large differences in traffic emissions. NO_x emissions will be 32% lower and PM emissions 13% lower in the *Regulated Shift* scenario compared to the *Free Play*. The data can be combined with other anthropogenic emissions for investigating air quality with chemistry transport models.

1. Introduction

Emissions from the transport sector account for a significant share of the global and regional greenhouse gas and key air pollutant burden, e.g. (Carslaw et al., 2016; Helmert et al., 2019; Kieseewetter et al., 2014; Uherek et al., 2010; Unger et al., 2008). Until today, transport by means of road, rail, water and air remains largely fossil fuel driven and represents a major contribution to greenhouse gases (GHG), namely CO₂ and air pollutants. Transport and particularly road traffic contributes significantly to air pollution through emissions of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) as well as precursors for secondary organic aerosols (SOA) and ozone. This directly affects the health of millions of people especially in larger cities and agglomeration areas (Kunzli et al., 2000; Lelieveld et al., 2015). Therefore, emissions from the road transport sector need to be characterized in detail and advanced data sets considering spatially varying traffic densities need to be made available for subsequent use in chemistry transport models. Here, we present a new model chain for calculating detailed gridded emission inventories resulting from road transport activities. It builds upon previous work and existing emission factors from the Handbook of Emission Factors (HBEFA), but extends this by non-exhaust emissions and emission factors for new driving technologies.

The share of transport emissions for greenhouse gases as well as for NO_x has been constantly increasing in Europe since 1990, partly because of emission reductions in other sectors, partly because of increasing road transport demand. Currently, road transport emissions are the single largest source of NO_x in the atmosphere (Karl et al., 2017). According to the European Environmental Agency

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(EEA) in 2016 transport contributed 27% to the total European CO₂ emissions (EEA, 2018). Concerning emission reductions, new technologies are emerging and existing technologies are being further enhanced with respect to energy efficiency. Engine concepts based on renewable energies or alternative less emitting fuels are slowly being introduced into the market. Furthermore, improved public transport concepts need to be established in many regions in order to reduce the individual transport demand.

Assessments of potential air quality improvements for certain scenarios in the transport sector should be based on advanced chemistry transport modeling to obtain temporally and spatially resolved concentration fields, which in turn can be related to health burdens. Chemistry transport models (CTMs) require as crucial input spatially and temporally resolved emissions of the relevant pollutants from the transport sector as well as from other sources which influence chemical transformations (Matthias et al., 2018). The improvement of emission deduction, scenarios and modeling is an important step towards reliable estimates of future air quality.

For Germany, to the best of our knowledge such a combination of spatially and temporally resolved transport and emission models that enable the calculation of future transport and air quality scenarios has not been attempted, yet. National transport models (e.g. BMVI (2014)), which are able to forecast travel demand, have been developed with a focus on infrastructure planning but they do not address issues of air pollution. Conversely, emission models are based on results from more aggregated transport models (e.g. in the Gridding Tool used by the German Environment Agency (UBA) (Schneider et al., 2016) with traffic data from TREMOD (Knörr et al., 2012, 2016) and cannot provide future scenarios with fine-grained spatially modified traffic patterns. The same holds for global emission data sets like the Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2018, 2016) that are available for years until 2012. Future scenarios for transport related emissions in the EU have been investigated from a health perspective (Essen et al., 2018), but here spatial information is missing.

The work presented in this paper attempts to bridge the gap and investigate air quality improvements by coupling an advanced chemistry transport model with fine-grained emission data from a transport model. For this purpose, a traffic emission inventory shall be produced on a $5 \times 5 \text{ km}^2$ grid for Germany and most of its neighboring countries. In the project “Transport and the Environment” (“Verkehrsentwicklung und Umwelt”, VEU) (Henning et al., 2015) three different scenarios of the German transport system up to 2040 are developed. The scenarios follow an explorative story and simulation approach and focus on micro-aspects that may be changed by national governments or through consumer behavior. The detailed scenario derivation is presented in Winkler and Mocanu (2020). The three scenarios are named *Reference*, *Free Play* and *Regulated Shift*. The *Reference* scenario has been defined along the framework parameters provided by the German planning document for transport (BMVI, 2014). The *Free Play* and *Regulated Shift* scenarios represent plausible and consistent options under similar macro conditions with regard to population, gross domestic product and crude oil price (Table 1). Storyline consistent measures, including financial provisions, incentives, tax and regulatory interventions are influencing the fleet size and composition, modal shares and travel behavior. They are thus two similarly likely options of possible developments of the transport system. As input to this work, the scenario storylines were transferred into modeling input parameters (for details see supplemental material in Winkler and Mocanu (2020)). New emission factors for road vehicles were developed including the addition of emission factors for plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV) (Seum et al., 2020). Similarly, the freight transport demand, freight transport fleets and modal shift have been modelled accordingly. In order to integrate the effect of emissions from electricity that is used for transport purposes, fleet-wide emission factors and factors for the energy demand of the German transport system today and in the future in 2040 were developed (Ehrenberger et al., 2020). Electrically propelled public passenger and freight rail transport and the grid-based electrically propelled passenger cars are contributing to emissions from electricity generation for transport. The explorative scenarios represent possible futures with a focus on plausibility and consistency of the context settings. The method presented here can be applied to other European countries, on the provision that traffic flows are spatially available on a sufficient level of detail.

This paper focuses on the spatial distribution of the transport emissions and compares the emissions resulting from an analysis of the three scenarios.

2. Modeling system

Investigating the effects of traffic emissions on air quality in Germany requires a combination of several models. Firstly, transport-related emissions need to be estimated sufficiently detailed and accurate for the entire country and its surrounding regions. Secondly, the emissions need to be distributed in time and space onto a grid used in the atmospheric chemistry transport model system. These models typically run on a larger area than the area of interest and consider the expected effects of emissions stemming from sources outside the area of interest.

A sketch of the modeling system employed in VEU is shown in Fig. 1. Traffic emissions were calculated in a bottom-up approach starting from scenario determined traffic flows stemming from the national transport model DEMO. The fleet composition and the emission factors for a number of relevant air pollutants as well as CO₂ were obtained from the vehicle stock model VECTOR 21,

Table 1
Characterization of the three scenarios as presented in Winkler and Mocanu (2020).

	Reference	Free Play	Regulated Shift
Storyline	Represents a continuation of currently existing trends, but also moderate improvements regarding the implementation of new technologies and the use of renewable energies (RE) in the transport sector.	Society follows a liberal market-economic logic. The state in this scenario takes a step back, trying to avoid hampering developments through an overburden of regulations.	Society implements more stringent regulations, combined with investments in infrastructure for public transport and financial instruments to foster the development of certain clean technologies.

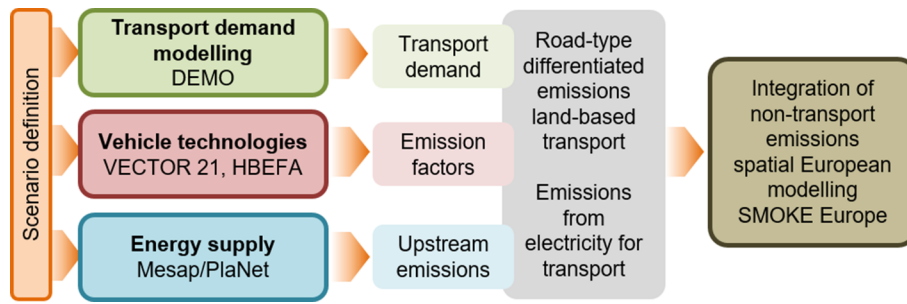


Fig. 1. Schematic flow-chart of the modeling system.

emission profile model HBEFA and an upstream modeling of the energy supply. The air pollutant emissions were then distributed in time for an entire year applying special time profiles. They were spatially distributed onto a $5 \times 5 \text{ km}^2$ grid suitable for chemistry transport model runs. These model components are described in the following sections. Since the spatial distribution of CO_2 emissions is irrelevant for climate effects, the analysis of CO_2 is not part of this paper.

2.1. DEMO transport model

Passenger and freight transport demand within Germany were modelled with the German national transport model DEMO for the base year 2010 and for future scenarios in 2030 and 2040. DEMO is a model landscape developed with the purpose of forecasting all types of traffic in Germany under the influence of social trends, technological advances and policy measures. It therefore encompasses several interacting tools for modeling passenger and freight transport demand.

DEMO is a largely synthetic, macroscopic model and relies on spatially disaggregated socio-demographic and land-use input data, such as population by age and employment, location of workplaces, economic indicators etc. It consists of separate modules for short- and long-distance passenger demand, freight transport demand, service traffic demand, and joint network assignment models for roads, rail and inland waterways. The transport demand modules (both for passengers and freight) loosely follow the classic four-step transport model template, running through trip generation, destination, and mode choice. The short-distance passenger demand module and the freight transport demand module both employ a trip-based approach, i.e. modeling each trip leg separately, while the long-distance passenger demand module and the service traffic demand module make use of a tour-based approach, i.e. modeling entire trip chains. A comprehensive description of the DEMO demand modules and the first three model steps can be found in [Winkler and Mocanu \(2017\)](#) and [Winkler and Mocanu \(2020\)](#), where a detailed analysis of the transport modeling results for all VEU scenarios is also presented. The final model step of trip assignment and its results are described in more detail in the following paragraph.

Within the process of trip assignment, passenger and freight origin–destination matrices, which are provided by the previous model steps, are loaded onto the transport networks, in order to derive traffic flows and loads at link level. The basis for the trip assignment procedure is a detailed network model. DEMO includes network models for roads, railroads and inland waterways. Network models provide comprehensive information on travel costs (travel time, distances etc.) that are essential inputs not only for trip assignment but also for modeling destination and mode choice. In the context of emissions calculations within the VEU project the focus was on a spatially highly detailed analysis of road transport. Therefore, only the road network model will be described, while rail transport and inland water transport are not considered in this paper. Nevertheless, greenhouse gas emissions from the latter two transport systems were considered in the project by either assigning traffic to the network (inland waterways) and by computing aggregated emissions from the transport demand and the corresponding electricity generation (rail).

[Fig. 2](#) provides information on the road network included in DEMO. Within Germany, the network density is visibly higher than in surrounding countries as DEMO does not only include highways and major national roads, but also parts of the subordinate network such as county and major urban roads. DEMO however does not include collector roads, since traffic on these links goes beyond the scope of a national transport model. For surrounding countries, the level of detail in the network is lower. In total, the road network of DEMO encompasses nearly one million links. Relevant attributes for the traffic assignment, such as road capacity, permitted speed, number of lanes etc. are set individually for each link according to the correspondence with one of more than 80 pre-defined road classes.

2.2. VECTOR 21 vehicle stock model

The model VECTOR 21 is a market simulation model for passenger cars ([Mock et al., 2010](#)). VECTOR 21 includes a vehicle stock module that builds on statistical data of vehicle ownership by technology and segments. Vehicle mileage curves and age distribution per segment size are used to calculate the fleet renewal and progression over time. Survival probabilities are differentiated according to vehicle sizes and annual mileage driven ([Ehrenberger et al., 2020](#)). The vehicle technology module of VECTOR 21 was used to analyze the market penetration of alternative drive trains under the framework settings of the three scenarios. VECTOR 21 combines an agent-based model with a discrete choice market penetration model and assesses the competition between different technology options ([Kugler et al., 2016](#); [Schmiecsek, 2015](#)). The European CO_2 target values for newly registered cars as average per manufacturer, the fuel taxes and the charging and fueling infrastructure are important determinants that influence the competitive position of different technologies.

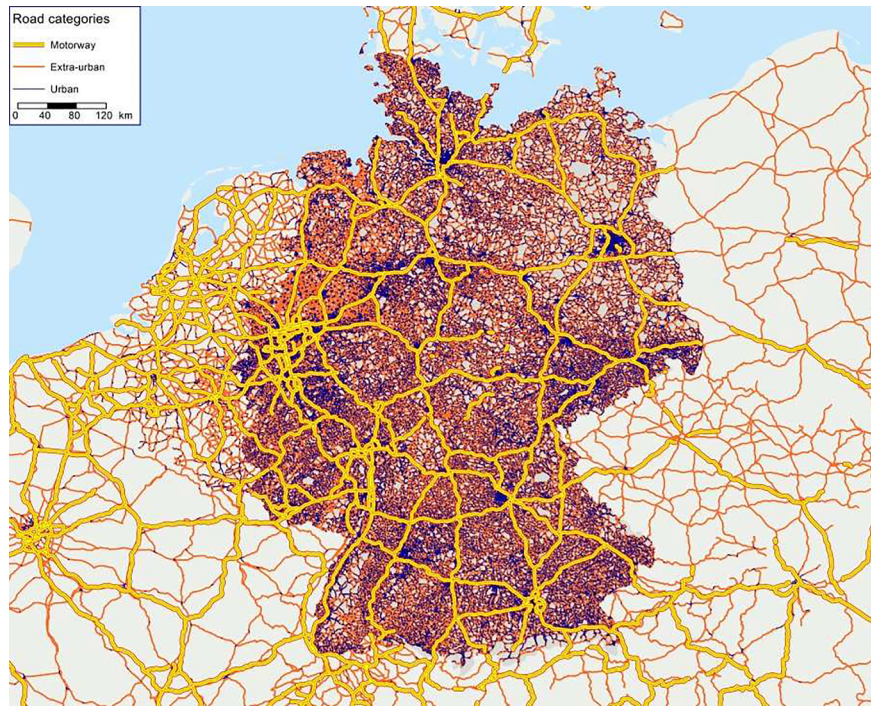


Fig. 2. DEMO road network divided into highways, rural and urban streets.

2.3. HBEFA emission factors

The Handbook of Emission Factors (HBEFA, 2017; Keller et al., 2017) in its version 3.3 serves as the basis for developing fleet-wide emission factors for vehicles. HBEFA offers realistic emission factors for real world conditions. The Handbook was originally developed based on the vehicle simulation model PHEM on behalf of the Environmental Protection Agencies of Germany, Switzerland and Austria (Hausberger et al., 2009). In the meantime, further countries (Sweden, Norway, France) as well as the JRC (Joint Research Center of the European Commission) are supporting HBEFA. Behind HBEFA emission factors is the coordinated research on emission factors in Europe, which is organized in the European Research Group on Mobile Emission Sources (ERMES), currently chaired by Technical University of Graz (Austria). The science behind ERMES feeds, besides HBEFA, also the emission model COPERT, commonly used on a European scale. The emission factors in HBEFA and COPERT are thus the widely accepted state of knowledge for real driving emissions. The reason of our choice for HBEFA are the possibility to compile specific vehicle fleet layers, differentiated by vehicle size, technology, emission standards and then aggregate them specifically for our scenario transport demand on urban, rural and highway roads. For the scenario years 2030 and 2040 the emission factors were expanded, including adding emission factors for PHEV and BEV vehicles, modifying the vehicle fleets and the energy system according to the scenario storylines. For this purpose, the model VECTOR 21 and an upstream modelling of the energy supply were applied (Ehrenberger et al., 2020). For the base year and the scenario years, non-exhaust emission factors for evaporation, road wear, tire wear and brake wear were reconsidered.

2.4. Energy scenario modelling

With the energy scenario model for Germany used, which was developed at DLR on the basis of the commercial software Mesap/PlaNet (Schlenzig, 1999), different scenario narratives can be quantified in the form of complete energy balances. For the estimation of future annual emissions, the model was extended by direct emission factors for thermal power plants and other stationary processes. The emission estimate for the years 2009, 2011, 2012 and 2014 could be calibrated with the official emission reporting of the German Federal Environment Agency (Ehrenberger et al., 2020). For the future, constant emission factors were assumed for each fuel and technology until 2040, which represents a conservative “worst case” scenario and takes into account that regulatory requirements in air pollution control are not known for the long-term future. Consequently, in our approach, future changes in average emissions from electricity supply are mainly a consequence of changes in the average generation mix. Depending on the total electricity demand and the deployment path for renewable energies, the generation mix leads to different average emissions of CO₂ and air pollutants. The results depend mainly on the assumed total share of renewable energies.

2.5. SMOKE for Europe emission model

SMOKE for Europe (Bieser et al., 2011) is an emission modeling system for Europe. It is based on the SMOKE model (Houyoux, 1998; Houyoux et al., 2000) developed and maintained at the University of North Carolina, Chapel Hill, USA. Its main purpose is to

spatially and temporally distribute emissions relevant for air quality onto a three dimensional grid with hourly data. This 4D data set is then used as input data for chemistry transport models like CMAQ (Byun and Schere, 2006). SMOKE for Europe typically uses national emission totals for certain species (e.g. NO_x, SO₂, CO, NH₃, HCs, PM) given for a number of emission sectors and distributes them with the help of proxy data like population density or land use onto a spatial grids with resolutions up to 1 × 1 square kilometer grid size. Then, temporal profiles are applied that consider typical time dependent modifications of the activities causing the emissions, e.g. diurnal and weekly profiles for traffic, seasonal profiles for agricultural emissions and temperature dependent cycles for heating. Lumped species like HC and PM are distributed to more detailed groups of substances according to the source category and the chemistry mechanism in use in the CTM. More details about underlying principles of emission modeling as used in SMOKE for Europe can be found in Matthias et al. (2018).

3. Base case 2010

The DEMO traffic model, HBEFA emission factors and the SMOKE for Europe model were applied for modeling traffic emissions in Germany for the year 2010. Details of the input data used in the models and the results of the model chain are described in the following section.

3.1. Traffic data

Fig. 2 shows the extent of the central study area with Germany in the center and parts of its neighboring countries. For modeling traffic with DEMO, Germany is subdivided into two sets of differently resolved traffic analysis zones (TAZ), a highly resolved set with 6,561 zones and a coarser resolved set with 412 zones, respectively. The former roughly correspond to the spatial level of municipalities and city districts whereas the latter represents the counties in Germany. The spatially more detailed 6,561 TAZ are used to model short-distance passenger transport, while the less differentiated 412 TAZ are sufficient for modeling transport demand for long-distance passenger and freight transport. However, in order to obtain more realistic traffic loads and origin–destination impedances (e.g. travel times, distances, costs etc.), the road traffic assignment procedure for both passenger and freight transport was carried out on the basis of the more detailed zoning system. For this purpose, the freight demand was spatially disaggregated from the 412 to the 6,561 TAZ. Since the focus of the project is on Germany, the traffic analysis zones of Germany's neighbors are less differentiated and grow larger with increasing distance from Germany. Incoming, outgoing and traffic through Germany is assigned in the model, and this approach can be applied to other countries as well when the zoning system is adapted.

In order to achieve realistic assignment results and costs on the one hand and to provide sufficient input data for subsequent emission calculations on the other hand, it is also necessary to consider several categories of vehicles within trip assignment procedures. Altogether eight categories are differentiated, three of them for passenger and five for freight transport:

Passenger transport:

- Short-distance passenger cars
- Long-distance passenger cars
- Coaches

Freight transport:

- Semitrailers
- Heavy duty vehicles (> 12 tons, except semitrailers)
- Trucks (between 7.5 and 12 tons)
- Trucks (between 3.5 and 7.5 tons)
- Light-duty utility vehicles (< 3.5 tons)

Detailed network information, such as free-flow speeds, speed limits, prohibited links or turns, is implemented in DEMO for each of these vehicle categories. On the basis of this information the necessary costs can be defined for each mode of transport. Most important are vehicle type-specific travel times, which are derived from road class-specific volume-delay-functions (VDF). There are 18 different VDFs defined for taking into account road-specific characteristics. Most of them are based on the BPR-function developed by the Bureau of Public Roads (1964), which is widely used in transport modeling. Function parameters were derived on the basis of theoretical investigations carried out by Wu (2000).

Within the VEU project the road transport demand was assigned using a procedure based on the Frank-Wolfe method (Frank and Wolfe, 1956), which is a widely used algorithm for defining equilibrium traffic flows for transportation networks. The concept and its application in transportation are described in detail, e.g. in Sheffi (1985). The assignment was carried out as a two-step multi-class assignment with a first step considering long-distance freight transport and coaches, since this traffic is characterized by the least flexible route choice. All other vehicle categories were subsequently assigned in a second step.

After the full DEMO model system was calibrated to fit observed road shares and trip length distributions, the traffic loads were calculated. Fig. 3 shows the results on the German network for the base year 2010. Indicated traffic loads are per direction. Most traffic occurs within the metropolitan areas of Berlin, Munich, Hamburg, Frankfurt (Main), Stuttgart and the Ruhr area. In these regions short-distance passenger trips are dominating. Furthermore, highways are also highly frequented, in particular between

metropolitan areas, but with a much higher share of long-distance and freight transport trips. Regions with little traffic are to be found in the less densely populated areas in North-East Germany.

3.2. Emission factors for road vehicles

The base-case emission factors and the fleet composition for road vehicles were taken from the Handbook of Emission Factors version 3.3 (Keller et al., 2017). The emissions included in the model are: the regulated emissions carbon monoxide (CO), nitrogen oxides and nitrogen dioxide (NO_x and NO_2), ammonia (NH_3), hydrocarbons (HC), particulate matter (PM)¹, and sulfur dioxide (SO_2). In order to address the spatial distribution of emissions, factors for three road categories – urban, rural and highway – were used. Emissions per street segment are thus the transport demand combined with the emission factors. For the base-year, the HBEFA car fleets were used. Two different sets of emission factors, one for warmer periods (20 °C ambient temperature) and one for colder periods (0 °C ambient temperature) were applied. In addition to the hot driving emissions we added additional exhaust and non-exhaust emissions such as cold start, evaporation, and wear emissions to each vehicle kilometer.

Most of the vehicles are only used for relatively short time intervals. More than 90% of the time, they are not in operation, however, they still have emissions from fuel evaporating from the tank. We used a temperature dependent algorithm (EEA, 2016) and hourly data from the meteorological model COSMO-CLM (Doms et al., 2011; Rockel et al., 2008) to calculate the evaporation. During summer time evaporation is the major source for HCs, albeit mostly less reactive and highly volatile alkenes. Finally, we implemented tire, brake, and road wear emissions. These are major sources for particulate matter emissions and are of high interest as they have the least reduction potential of all transport related emissions (Amato, 2018). We implemented emission factors depending on road category and vehicle weight. For each wear type we used distinct speciation and size profiles (Baensch-Baltruschat et al., 2020; Grigoratos and Martini, 2014, 2015), see Table 2. For further use in chemistry transport model calculations we divided the emissions into particles with diameter less than 2.5 μm ($\text{PM}_{2.5}$) and those with diameters between 2.5 μm and 10 μm ($\text{PM}_{\text{coarse}}$).

3.3. Emission factors for non-road traffic

Base-year emission factors for rail and inland water transport were taken from TREMOD (Knörr et al., 2012, 2016). The emissions for rail and inland water transport were calculated based on passenger and ton kilometer transport activity. Additional information on utilization rates for rail services was taken from Deutsche Bahn (2011) and Verband Deutscher Verkehrsunternehmen (VDV) (2011).

Fig. 4 shows the share of the emissions originating from different stages of driving. Most of the emissions like CO, NO_x and small particles ($\text{PM}_{2.5}$) are caused by hot combustion processes. They are unwanted by-products of the engine operation. Cold starts are responsible for almost 20% of the total CO and HC emissions while evaporation causes more than half of all HC emissions. Brake, road and tire wear are an important source of PM emissions. More than 80% of the coarse particles larger than 2.5 μm diameter stem from this activity. It should be noted that these emissions are not expected to decrease significantly when new propulsion systems will be implemented in the future.

3.4. Emission data for chemistry transport models

For computing the effect of traffic emissions on air quality in Germany, emissions need to be spatially distributed. This mostly means that they need to be gridded according to the resolution of the chemistry transport model that will take these emissions as input. In addition, a temporal distribution needs to be applied. Traffic emissions show a clear temporal variation on multiple time scales. Daily variations are mainly caused by commuter traffic with a clear and relatively narrow morning peak and a somewhat broader evening peak. In addition, traffic is much lower on weekends compared to working days and modified daily profiles apply. This very uniform variation with a weekly cycle can be seen in Fig. 5 for HC emissions from hot combustion. Besides this standard time profile that was taken from Denier van der Gon et al. (2011), cold start emissions and evaporative emissions depend on ambient temperatures. They can therefore be modelled by considering meteorological data. This data is anyway needed for subsequent atmospheric chemistry transport modeling and it is therefore available on an appropriate horizontal geographical grid. Fig. 5 includes the annual profile of HC emissions. They were calculated with the SMOKE for Europe emission model and then spatially averaged over Germany. The temperature dependent approach for evaporative emissions is applied in several thousands of grid cells of $5 \times 5 \text{ km}^2$ each, which leads to a distinct spatial and temporal distribution of emissions in each grid cell of the model domain. Weekday/weekend variations are considered for all emission categories. It can be clearly seen that higher emissions occur in summer when ambient temperatures are higher. The ratio between average summer (July) and winter (January) emission levels is approximately 2.

The traffic emissions produced with DEMO were spatially distributed according to the street map used in DEMO. SMOKE for Europe distributes these emissions horizontally on a rectangular grid taking into account the lengths of specific street segments in the respective model grid cell. Fig. 6 shows the spatial distribution of vehicle kilometers for the three road types highways, rural and urban. Based on this, the emission distribution from traffic is calculated on a $5 \times 5 \text{ km}^2$ grid for entire Germany for CO, NO_x , HC, NH_3 , SO_2 and PM. Fig. 7 exemplarily shows the spatially resolved results for NO_x . Areas with high population densities and large

¹ According to HBEFA: PM “is defined as “any material collected on a specified filter medium after diluting the exhaust with clean filtered air so that the temperature does not exceed 325 K (52 °C).” (Hausberger, S., Rexeis, M., Zallinger, M. & Luz, R. (2009) *Emission Factors from the Model PHEM for the HBEFA Version 3.*)

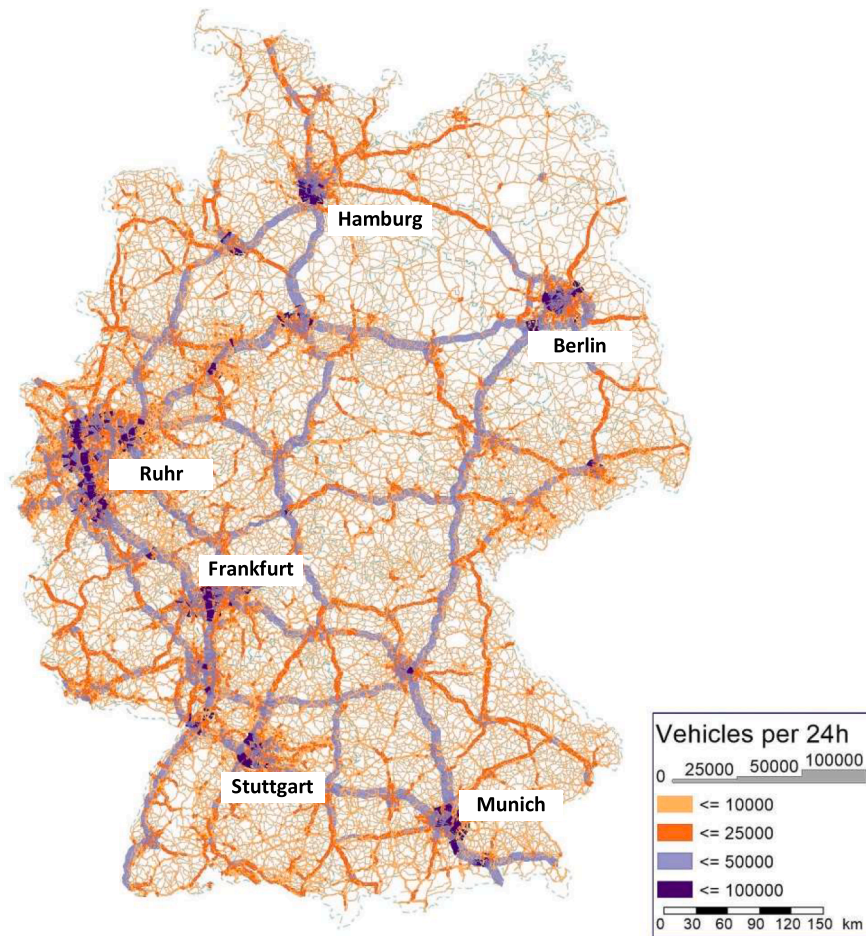


Fig. 3. Road traffic loads calculated with the DEMO model system for Germany in 2010.

Table 2

Emission factors for brake wear, road wear and tire wear used in VEU for vehicles below 3.5 t and above 3.5 t gross vehicle weight. All values are in mg/km.

Street type	Species	Brake wear		Road wear		Tire wear	
		> 3.5 t	< 3.5 t	> 3.5 t	< 3.5 t	> 3.5 t	< 3.5 t
Urban	PM10	42	12	300	300	70	14
	PM2.5	16	7	3	1.5	50	10
	SO ₂	–	–	–	–	0.0004	0.00004
	HC	–	–	–	–	0.012	0.0012
Rural/highway	PM10	22	7	200	20	35	7
	PM2.5	8	3	2	1	25	5
	SO ₂	–	–	–	–	0.0002	0.00002
	HC	–	–	–	–	0.006	0.0006

traffic volumes can be clearly identified. Lowest emissions are found in Northeast Germany and largest in the western and south-western part of the country.

The emission totals derived with the bottom-up approach described here were compared to those reported in the EMEP (Co-operative program for monitoring and evaluation of long range transmission of air pollutants in Europe) emission inventory (EMEP Centre on Emission Inventories and Projections (CEIP), 2015), see Fig. 8. The data for Germany is provided by the German Environment Agency (German Environment Agency (Umweltbundesamt), 2020). CO and NO_x are the main species emitted. While the estimates for CO are about 20% lower than those in the EMEP inventory, NO_x is about 15% higher. HC and NH₃ emissions are also higher in the new inventory, HCs mainly because the emissions from evaporation have been reconsidered. For PM, the totals remain almost unchanged but a shift towards coarser particles was found. This is connected to the emission factors for street wear, tire wear, and brake wear that were used in this study's approach.

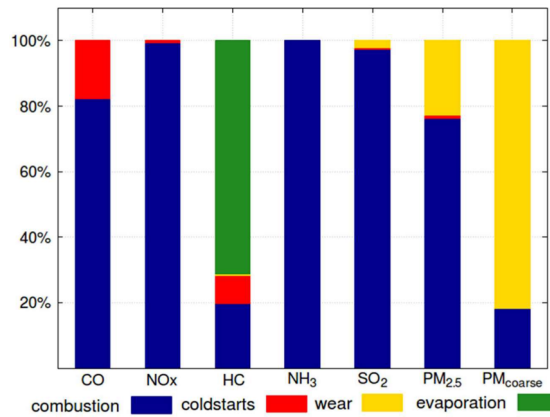


Fig. 4. Share of emissions connected with hot combustion (blue), cold starts (red), brake, road and tire wear (yellow) and evaporation of fuel from the tank (green) for 2010 in Germany calculated with the DEMO-HBEFA-SMOKE for Europe model chain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

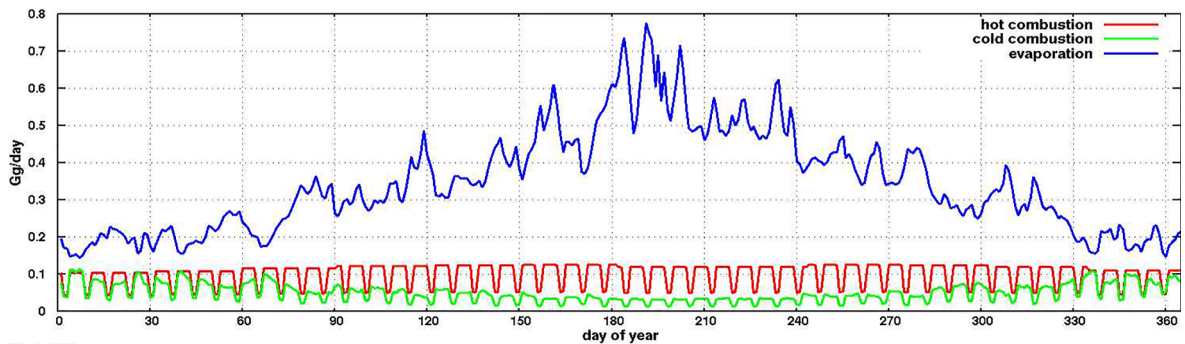


Fig. 5. Daily emission sums of hydrocarbons from traffic in Germany in 2010, separated into hot combustion, cold starts, and evaporation. HC emissions from tire, brake and street wear are very small and not included here. The emissions displayed are spatially averaged values for Germany.

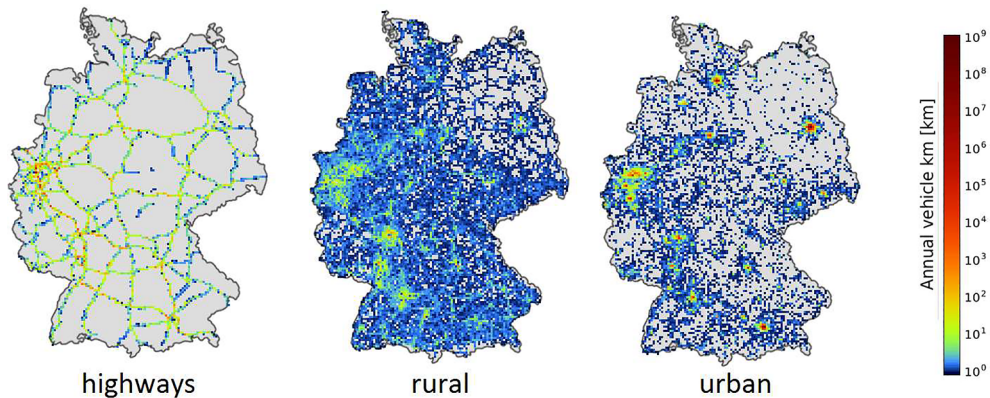


Fig. 6. Spatial distribution of traffic intensities in annual vehicle km in Germany on $5 \times 5 \text{ km}^2$ grid in 2010 based on DEMO model results. Given are highways, rural and urban streets.

4. Future scenarios

4.1. Fleet development

Our three future scenarios are explorative scenarios building on a story and simulation (SAS) approach as recommended by the German Environment Agency (Weimer-Jehle et al., 2011). The process of our SAS approach included literature reviews and a series of workshops with more than 30 experts from various fields. First, outlines (“stories”) of possible futures in Germany 2030 and 2040 were imagined (see Table 1) and crucial scenario parameters and their possible ranges of developments consistently plotted. As mentioned,

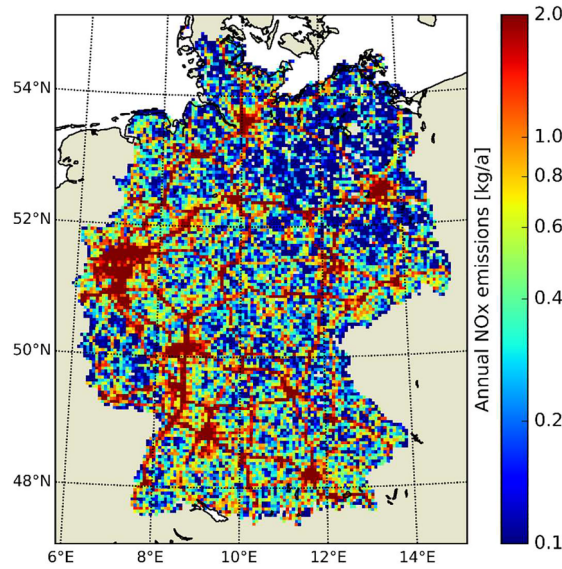


Fig. 7. NO_x emissions in kg/year (kg/a) per grid cell of 5 × 5 km².

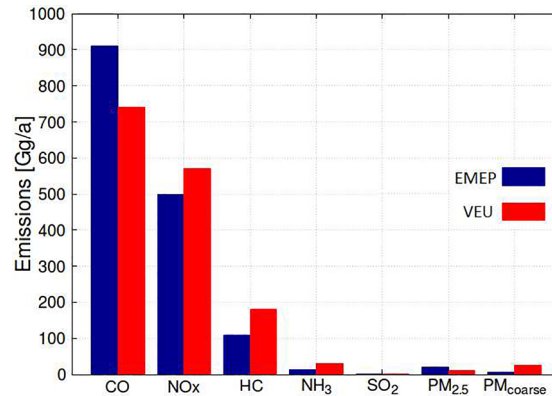


Fig. 8. Traffic emissions in 2010 in Germany for CO, NO_x, HCs, NH₃, SO₂, PM_{2.5} and PM_{coarse} calculated with the VEU bottom up approach and with the SMOKE for Europe model based on EMEP data. Annual totals are given in Gigagrams/year (Gg/a).

we focused on micro scenario parameters that may be changed by politics or consumer behavior, while leaving the macro aspects population, economy and crude oil prices equal for all scenarios. The possible combinations of scenario parameters were analyzed using a cross impact balancing (CIB) approach (see e.g. [Weimer-Jehle et al. \(2016\)](#)). From CIB, nine fully consistent combinations of scenario parameter developments emerged, of which three most diverging were selected to draft the VEU scenario storylines. As a last step, the scenario storylines were operationalized in order to identify the appropriate input parameter for the modeling network. The full process is described in [Seum et al. \(2017\)](#), [Seum et al. \(2020\)](#) and the supplemental material in [Winkler and Mocanu \(2020\)](#). In the following, the scenario effects on the future fleets is described exemplary. We hereby focus on the year 2040 for simplification. The fleet composition with regard to number of vehicles and size of engine as well as technology plays an important role for the resulting transport emissions. Several modelled micro-aspects (policy measures and behavior) have an impact on car ownership and on vehicle fleets in the future. One example are developments in the *Regulated Shift* scenario, where policies promote walking and biking through infrastructure investments and public transport through investments and pricing schemes together with sharing concepts, by at the same time making private car ownership more expensive, e.g. higher fuel and car taxes, and parking less available through a reduction in urban parking spaces and higher costs. Consistent with the scenario storyline, the consumer embraces more sustainable live styles and takes advantage of sharing options and active modes. The implemented levers were translated into modeling parameters (e.g. access time to private vehicle, car-ownership decisions of certain cohorts etc.) and analyzed in e.g. a spreadsheet vehicle fleet model. Particularly the cost regimes are important input parameters in the vehicle technology model VECTOR 21. Cohort effects and behavior changes lead for example to a total of 43 million passenger cars in the *Reference* scenario (560 cars/1000 population), whereas in the *Free Play* scenario 45 million and in the *Regulated Shift* scenario 35 million (460 cars/1000 population) are on the road ([Winkler and Mocanu, 2020](#)). With regard to vehicle technology, 17% PHEV and 3% BEV passenger cars are in the market in the *Reference* scenario, for *Free Play* scenario PHEV are below 2% and no BEV cars and in *Regulated Shift* 30% PHEV and 15% BEV cars dominate the fleet ([Ehrenberger et al., 2020](#)).

The developments of public transit options were analyzed likewise, adjusting occupancy, access time, speed and efficiency according to the scenario storylines. Freight transport has been analyzed with a fleet model approach as well and here natural gas trucks are present in the *Free Play* scenario, and in the *Regulated Shift* scenario a large portion of the long distance trucking is electrified using overhead lines on major highways (Ehrenberger et al., 2020).

The modeling of passenger transport demand uses primarily econometric parameters for its projections (Winkler and Mocanu, 2020). For example, the above stated aspects result in different costs of mobility as well as in different access and performance times. The technological progress is also determined largely by different cost regimes (Mock et al., 2010). As input figure, we projected the future car ownership and car size trends for the three scenarios.

4.2. Traffic forecast

For each future scenario DEMO was used to forecast passenger and freight transport demand on the basis of scenario-specific developments and measures.

The impact of the scenario-specific measures on transport demand in terms of number of trips, mode shares and distance (vehicle kilometers) travelled for both passenger and freight transport is discussed in detail in Winkler and Mocanu (2020). The forecasted vehicle kilometers travelled (VKT) by road, which are relevant for the emission modeling, are shown in Fig. 9.

In summary, road traffic will increase by ca. 25% in the 2040 *Reference* and *Free Play* scenarios compared to 2010, mainly due to increased motorization rates, economic growth, and improved vehicle fuel efficiency. Even in the *Regulated Shift* scenario, traffic will increase compared to 2010, albeit by only 7%. The dampened increase in this scenario is achieved by measures leading to increased costs for road transport users and improvements in the alternative modes. Further details on the scenario-specific measures and their impact are given in Winkler and Mocanu (2020).

Since the emission modeling requires spatially fine-grained traffic data, in this section we will focus on results from the DEMO network assignment model, i.e. the distribution of traffic flows onto the German road network. Transport networks and policy measures related to the infrastructure have impacts on all transport demand related choices. However, route choice, which is considered here, is most directly influenced. Variations in the scenarios pertaining to road infrastructure are based on the Federal Transport Infrastructure Plan (Bundesverkehrswegeplan, BVWP) (Bundesministerium für Verkehr und digitale Infrastruktur, 2016), which is the key regulation element of the German Federal Government for the development of the German transport networks. It distinguishes projects by their priority based on a project evaluation process, whereby projects are differentiated between the construction of new infrastructure and the expansion of existing elements. The most recent BVWP is the BVWP 2030, which has a time horizon until the year 2030. The BVWP 2030 succeeded the former BVWP 2015 during the VEU project term, which is why both plans had to be considered in the project. However, many projects are included in both plans, since they have not been realized up to now. The concept and method of the new BVWP 2030 is briefly described in Walther et al. (2015).

Concerning the road network the scenarios differ as follows:

- *Reference* and *Free Play* scenarios: Implementation of all first priority projects from the BVWP 2015 which are listed as first priority in the BVWP 2030 (both construction of new roads and expansion measures)
- *Regulated Shift* scenario: Implementation of BVWP 2015 projects either already under construction in 2015 or with secured financing according to the BVWP 2030, and all other expansion measures from the BVWP 2030 (but not construction of new roads)

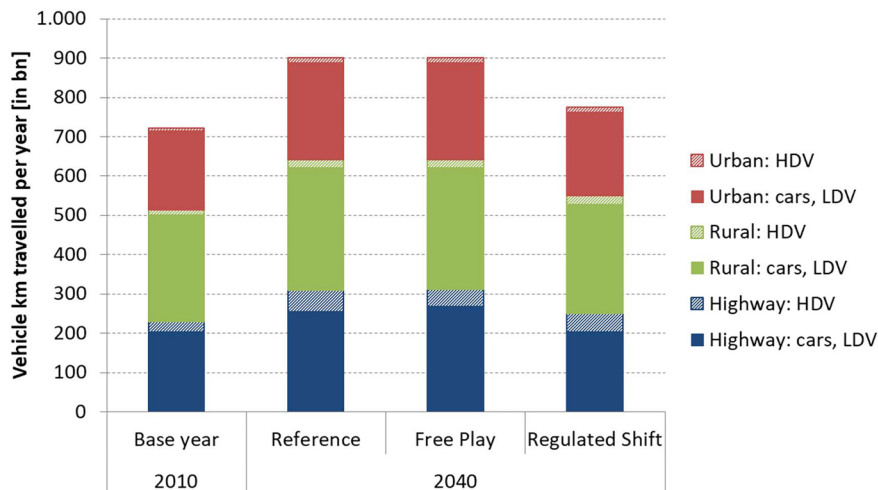


Fig. 9. Development of the travelled kilometers by heavy duty vehicles (HDV) on the one hand and light duty vehicles (LDV) and passenger cars on the other hand in the three scenarios, split into the street types urban, rural and highway.

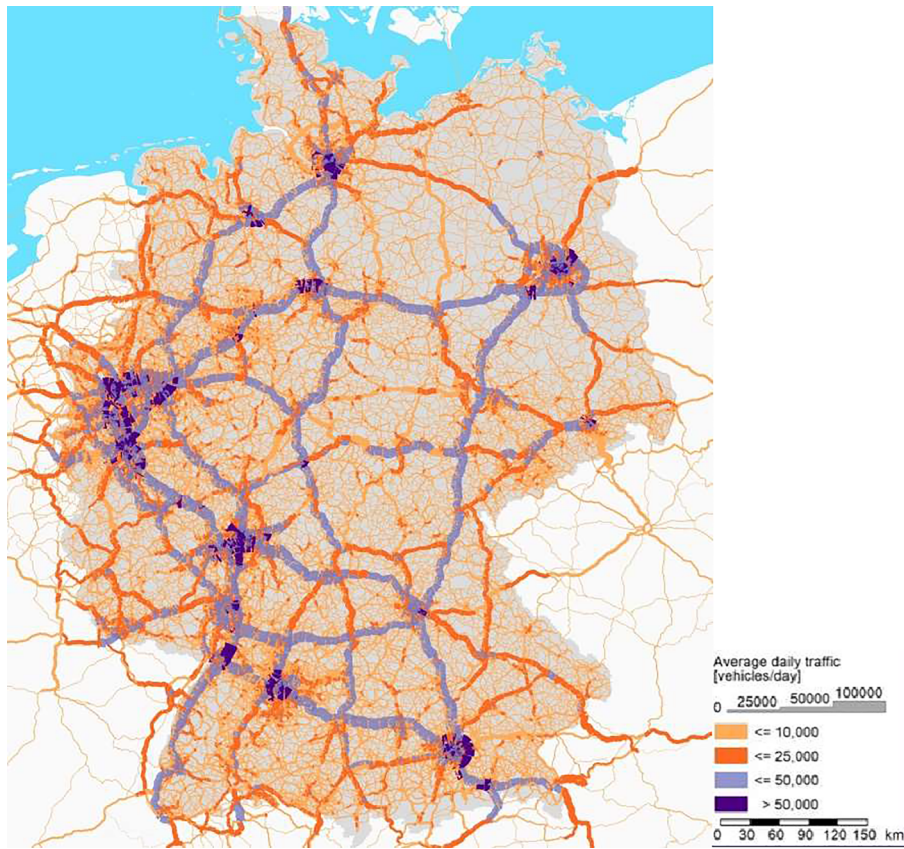


Fig. 10. Road traffic loads for an average day (24 h) in the 2040 Reference scenario.

These assumptions lead to the same road network being employed in the *Reference* and *Free Play* Scenarios, which is built on a “finalization” of the BVWP 2015 and BVWP 2030 measures. The road network in the *Regulated Shift* Scenario is less developed; particularly there are no significant new major roads.

Fig. 10 shows the forecasted traffic loads on the road network for the 2040 *Reference* scenario, while Fig. 11 shows the differences in traffic loads between the *Reference* and the other two 2040 scenarios. Compared to the *Reference* scenario, traffic will decrease in the *Regulated Shift* scenario due to mode shift towards rail and public transit and a reduced vehicle stock. It should be noted that this is achievable even with a less developed national road infrastructure (e.g. two new north–south oriented highways in the center-northern region are missing in this scenario). The decrease in traffic is most visible in the large metropolitan areas and along the major highways, and is due to the many different measures for shifting transport demand from motorized road transport to other modes (for further details on the corresponding travel demand see Winkler and Mocanu (2020)). The differences in traffic loads between the *Free Play* and *Reference* scenarios are much lower, since the overall VKT are similar and the road network is identical in both of these scenarios. Moderate traffic increases can be observed in the large metropolitan areas and along the highways connecting important industrial areas and sea ports, while loads very slightly decrease on rural roads.

4.3. Future emission factors

The emission factors for the transport scenarios represent different fleet compositions with regard to size, engine distribution and to additional technologies. In the case of conventional gasoline and diesel vehicle technologies, we built upon the 2030 emission factors from the handbook of emission factors (HBEFA 3.3) assuming all conventional vehicles in 2040 are EURO 6 vehicles. Furthermore, we enhanced the database by introducing hybrid, plug-in hybrid and battery electric technologies (the latter for determining the energy consumed (Seum et al., 2020)). Final car fleet compositions were modelled with the VECTOR 21 model according to the VEU scenario storylines (Ehrenberger et al., 2020). Emission factors for light and heavy duty vehicles were developed in a similar fashion. The meteorological data set for 2015 was also used for modeling evaporative emissions in 2040, i.e. emission changes caused by climate change were not considered.

As for air pollutant emissions, in particular CO, NO_x (as NO₂) and PM, hot driving emission factors for conventional technologies decline in the future due to stricter emission regulations. Fig. 12 shows exemplarily the modelled progression of Euro-Emission-Standards and the introduction of hybrid and electric drives in the VEU *Reference* scenario. The emission factors of plug-in hybrid electric vehicles (PHEV) are based on own measurements of emissions of a mid-size PHEV on the DLR vehicle test bed (exemplarily

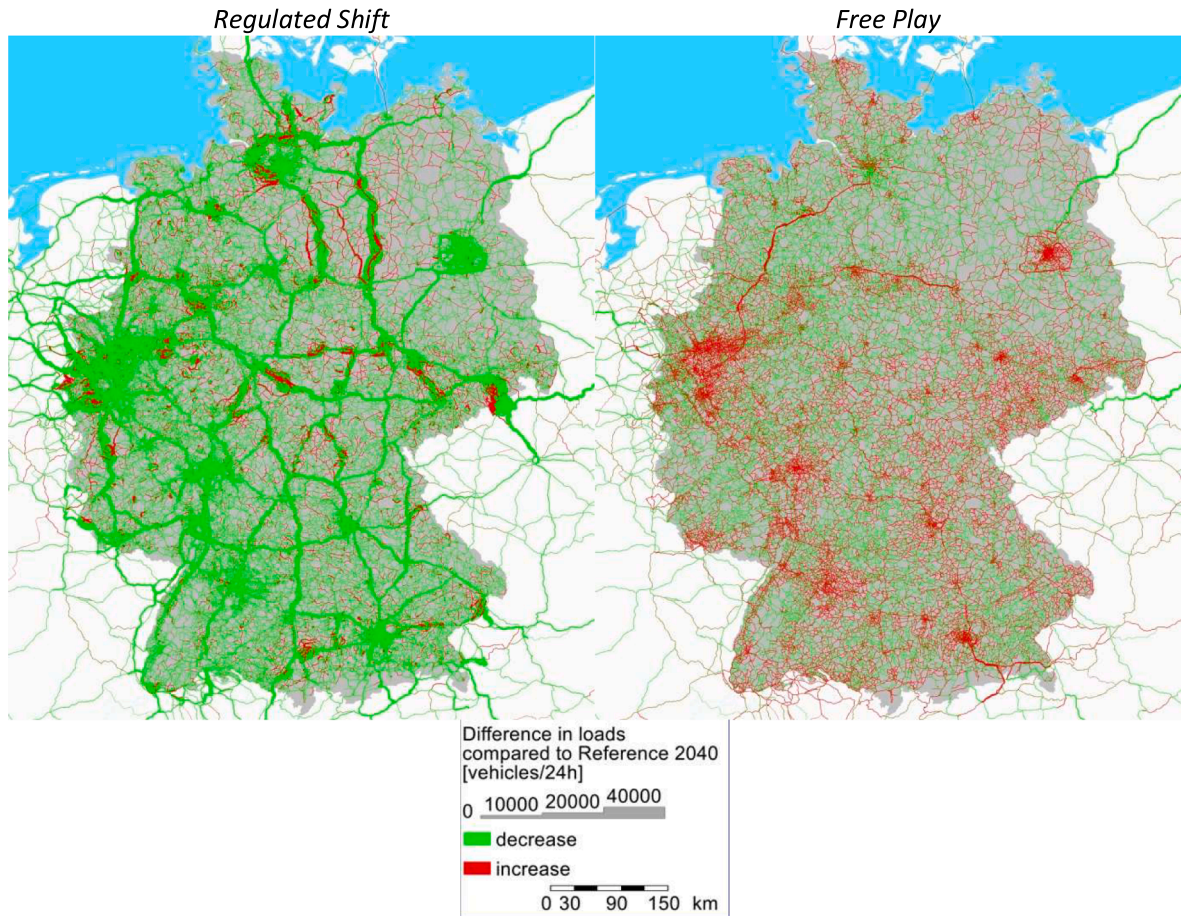


Fig. 11. Differences in road traffic loads in the 2040 Regulated Shift (left) and Free Play (right) scenarios, compared to the 2040 Reference scenario.

described in Kugler et al. (2016)). These measurements delivered the emissions for the different road categories and temperatures as well as a utility factor to take into account the different electric driving shares in urban, rural and highway driving situations.

The final VEU-scenario emission factors are a combination of technological progressions and the change in fleet compositions as described in Seum et al. (2020) and total emission from each mode is presented in Ehrenberger et al. (2020). Due to technology improvements, the NO_x emissions per kilometer from conventional vehicles will decrease in all scenarios. A further reduction considering the entire fleet is achieved through an increasing share of electric driving in particular in the *Regulated Shift* scenario. However, NO_x emissions per kilometer remain higher for vehicles using a diesel engine, both in the case of conventional and hybrid electric vehicles. Thus the NO_x emission factors for an average passenger car in 2040 remain approximately twice as high in the *Reference* scenario and the *Free Play* scenario compared to the *Regulated Shift* scenario. Furthermore, as an effect of increasing the diesel fuel tax to equal levels with the gasoline tax in the *Free Play* scenario, the share of diesel and diesel hybrid passenger cars is

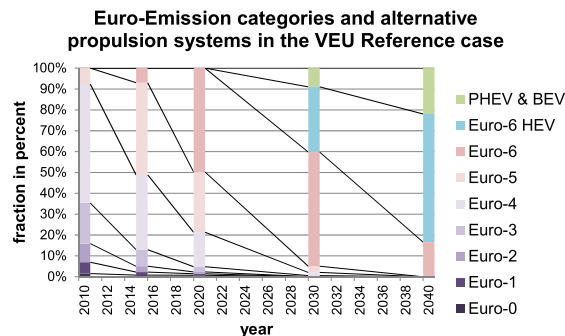


Fig. 12. Progression of passenger vehicle emission-standards (Euro-0 to Euro-6) and new propulsion technologies (hybrid electric vehicles (HEV), plug in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV)) in the VEU Reference scenario.

lower than in the *Reference* scenario. This leads to higher NO_x emissions per passenger car kilometer in the *Reference* scenario compared to the *Free Play* scenario (Ehrenberger et al., 2020).

We added cold start emissions in the same way we did this for the base case. However, as hybrid technologies will be introduced into the fleets and since longer cold start phases of hybrid technologies may be expected, this phenomenon may become more important in the future. Despite of this, we did not consider any increase in cold start emissions because of the lack of sufficient knowledge. This topic surely warrants more research in the future.

For the electrified transport modes and vehicles we applied the upstream emission factors from the German power generation system. The progression of the electricity mix was modelled using the DLR energy system model for Germany (Ehrenberger et al., 2020). The shift from fossil fuels to electric energy can significantly reduce greenhouse gas and pollutant emissions. The degree of beneficial effects depends on the long-term development with regard to the shift towards renewable energy sources, driven by the targets of the German energy transition ('Energiewende'). Consistent to the scenario storylines, we therefore assumed different developments of the power system for the three VEU-scenarios. A successful continuation of the German Energiewende, i.e. target-oriented expansion of renewable energies in power generation results in around 78% renewable electricity in 2040 in the *Regulated Shift* scenario (according to the long-term scenarios in Pregar et al. (2013)), whereas this share is 60% in the *Reference* scenario according to Schlesinger et al. (2014) and assumed to be only 40% in the *Free Play* scenario, corresponding to a halt to the further expansion of renewables after 2020. However, NO_x and CO emissions from central power stations providing electricity for transport remain a significant source (Seum et al., 2020).

5. Scenario discussion

We focus the discussion on changes in the most critical air pollutants in Europe, namely nitrogen oxides and PM. In all scenarios for 2040 absolute emissions of NO_x from traffic in Germany decrease by about 80% compared to 2010 (see Fig. 13). This corresponds with other studies, demonstrating that the implementation of advanced exhaust-after-treatment will result in significant NO_x emission reductions (e.g. (Borken-Kleefeld and Ntziachristos, 2012; Knörr et al., 2016)). Largest reductions (−86%) can be expected in the *Regulated Shift* scenario and lowest in the *Reference* scenario (−77%). In a comparative view, the *Reference* scenario shows higher NO_x emissions than the *Free Play* scenario because more diesel cars stay in the market because diesel fuel is still incentivized through lower taxes on the fuel. In 2010, the largest contributions are direct emissions from cars and from freight transport, each holding approx. 45% of the total. In 2040 freight transport is expected to still contribute about 45% to the NO_x emissions in the *Reference* and *Free Play* scenarios. The share of NO_x emissions from cars is reduced, but this is almost completely compensated by NO_x emissions caused by electricity production. Only in the *Regulated Shift* scenario, with a high amount of renewable electricity production, NO_x emissions would be further reduced because of the shift towards electricity use in the transport sector.

For PM, the situation is quite different. According to the estimates presented here, brake and tire wear as well as resuspension from streets contribute the largest fraction to the PM emissions from traffic. While exhaust gas related PM emissions decrease even further than NO_x emissions, depending on scenario by 82–88% (see Fig. 13), non-exhaust emissions increase by 14–31%, with the lowest values in the *Regulated Shift* scenario. This is connected with an increase in VKT by 27% in the *Reference* and *Free Play* scenarios and 10% in the *Regulated Shift* scenario (see Fig. 9). In none of the scenarios measures to reduce non-exhaust PM emissions were considered.

The uncertainty in those projections stem from different levels, including transport demand and performance of advanced vehicle technologies. For example, transport demand might be affected by macro-economic parameters. The scenarios however should be compared mostly in reference to each other. Increasing population would affect all scenarios equally. More difficult to assess are the uncertainties due to emission performance from advanced vehicles. Here particularly the real emissions of PHEV vehicles are of concern. First, reality must proof the share of electric driving. Second, as discussed earlier, PHEV may have different emission behavior in short distance trips with many engine on and off cycles. The setting of emission factors followed a rather conservative path and discussion can be found in Ehrenberger et al. (2020) and Winkler and Mocanu (2020).

Uncertainties concerning non-exhaust emissions are still rather high. The systematic evaluation of existing data suffers from a missing established terminology and the large variability in the conditions and results of available field studies (Padoan and Amato, 2018). Further research is definitely necessary for all the contributions, i.e. road dust resuspension, tire, brake, clutch and road wear. While for electrical cars it is still unknown to what extent regenerative braking reduces wear, their increased weight due to heavy batteries is considered to lead to significant contributions to PM emissions (Timmers and Achten, 2018). As exhaust emission controls become stricter, relative contributions of non-exhaust sources to traffic-related emissions will become more significant and may account for up to 90% of total PM emissions from traffic within a decade (e.g. Grigoratos and Martini (2015), Squizzato et al. (2016)).

In all scenarios NO_x emissions are largely reduced on all road types. Largest reductions can be seen in areas with highest traffic, like the Rhine-Ruhr area and the largest cities Berlin, Hamburg, and Munich (see Fig. 14). Differences between the scenarios are small when the *Reference* and the *Free Play* Scenario are compared (Fig. 15 a)). On the other hand, the *Regulated Shift* scenario shows additional reductions in densely populated areas and on highways while increasing emissions compared to the *Reference* scenario are visible outside of large cities (Fig. 15b)).

6. Summary and conclusions

Traffic emissions in Germany were calculated in a bottom-up approach for the year 2010 and for three scenarios for 2040 using a novel network of models, including transport demand, energy system, vehicle technology models and a modified emission model. Significant enhancements were made by taking brake and tire wear as well as street wear into account. In addition, evaporative emissions from tanks were considered depending on ambient temperature. Emission factors for plug-in hybrid electric vehicles (PHEV)

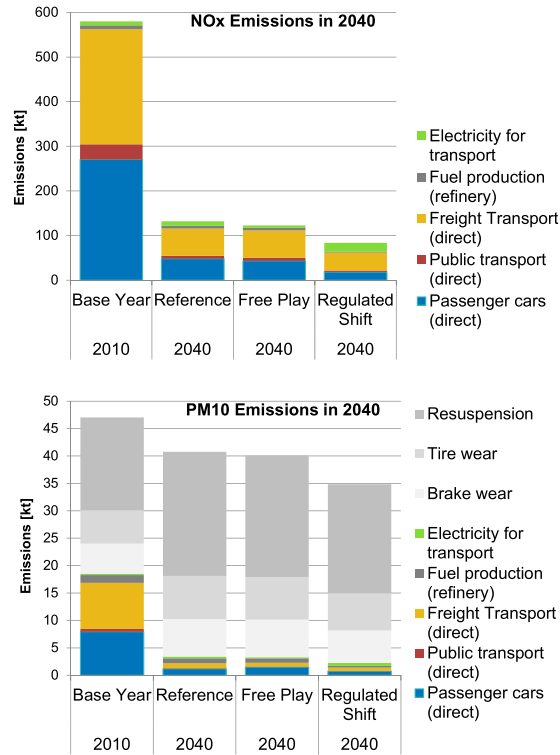


Fig. 13. Development of nitrogen oxide (NO_x) and particulate matter (PM_{10}) emissions between 2010 (base year) and the three scenarios for 2040. Transport electricity refers to emissions from power plant providing electricity for transportation. Transport refinery refers to emissions from crude oil refining process for transport fuels.

were added based on new laboratory measurements. Gridded emissions on a $5 \times 5 \text{ km}^2$ grid have been produced along with temporal emission profiles that take weather conditions into account, leading to more realistic spatio-temporal emission distributions.

One of the main features of the new model system is that emission scenarios can be constructed that include modifications of the traffic flows, changes of the fleet including new technologies, and the share of engine sizes. All these future changes may be applied in a different way in cities compared to less densely populated areas and in a different way for freight transport than for individual traffic, leading to spatially varying emission changes. The model system has been used for constructing three traffic emission scenarios for the year 2040 which reflect certain policies and consistent possible societal developments with regard to street traffic. Possible non-road emission changes, e.g. from inland navigation were not considered because of the small changes expected.

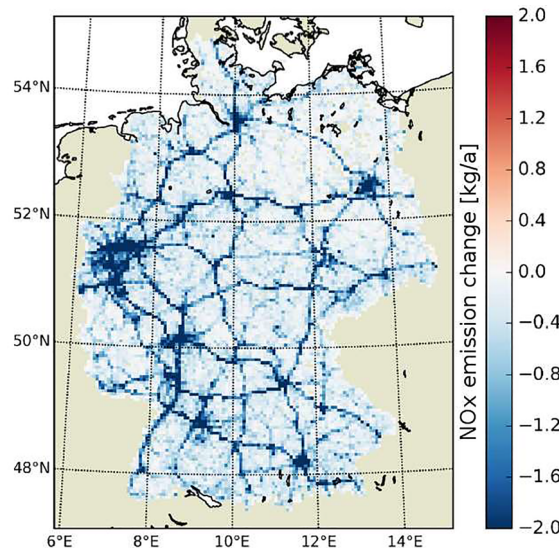


Fig. 14. Spatial distribution of the NO_x emissions changes in 2040 compared to 2010.

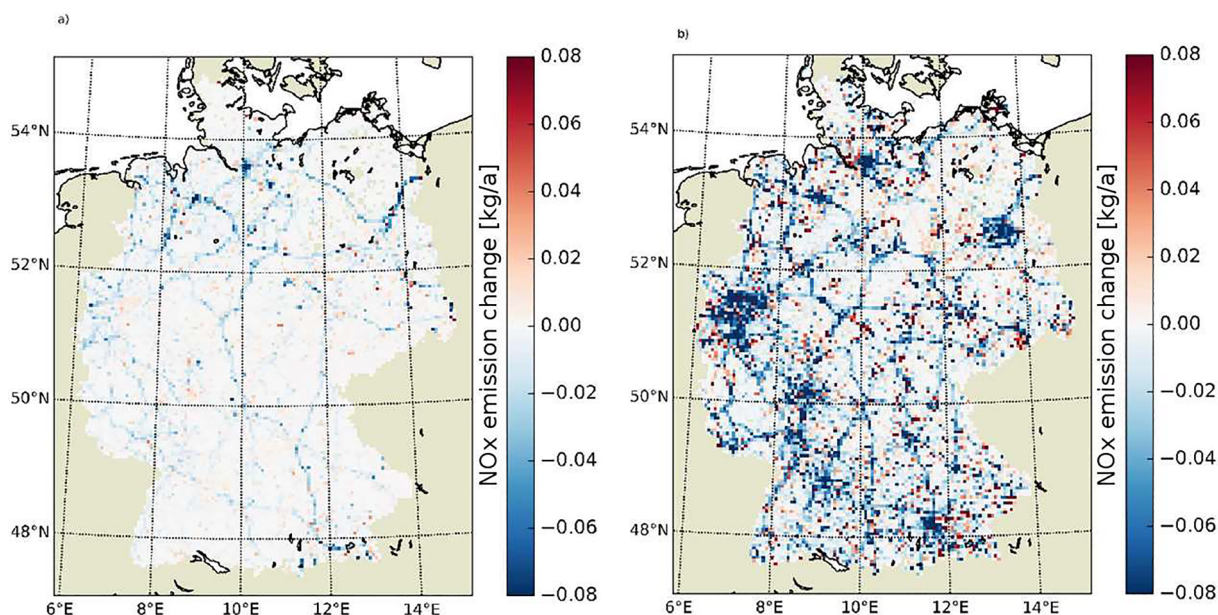


Fig. 15. NO_x emission changes for the Free Play scenario (a) and the Regulated Shift scenario (b), both as difference to the Reference scenario in 2040.

With respect to the most critical air pollutants in Europe, NO_x and PM, it was found that direct NO_x emissions from traffic can be expected to decrease by approximately 80% until 2040 while PM emissions show a much lower reduction. This is caused by the fact that direct particle emissions from traffic are dominated by brake, tire and street wear. It is not expected that these emissions will largely decrease because total travelled distances increase in the *Free Play* and the *Reference* scenarios. In addition, pure electric cars that use energy recuperation for slowing down still have a low share in all scenarios for 2040. PM emissions from engine operations will be significantly reduced in all scenarios but they can only partly compensate increased wear emissions.

Despite the large reduction in 2040 compared to 2010, the future scenarios *Free Play* and *Regulated Shift* represent large differences in traffic emissions. NO_x emissions will be 32% lower in the *Regulated Shift* scenario compared to the *Free Play* and PM emissions will be 13% lower.

With regard to passenger transport, this additional reduction can be attributed approximately half to behavior change (mode shift, less car travel) and half to technology (more BEV and PHEV vehicles). With regard to freight transport, the additional reduction comes to 90% from technological measures, i.e. the electrification of long-distance trucking. We can conclude that behavior changes are important, particularly for passenger transport and particularly in urban areas, but must be paralleled by technological measures to increase societal benefits.

Traffic outside Germany was not considered here, however, with the necessary adjustments and the specific input data the here introduced approach could be applied to model traffic emissions for other countries as well. Gridded and time resolved emissions from traffic can be combined with other anthropogenic emissions and then fed into chemistry transport models for calculating their impacts on air pollution levels. Such model systems include interactions with other pollutants and consider the complex and non-linear atmospheric chemistry. Spatially non-uniform emission reductions as they can be expected until 2040 will lead to concentration reductions that can hardly be estimated from national totals alone. This will be investigated in a follow-up study.

CRedit authorship contribution statement

Volker Matthias: Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing. **Johannes Bieser:** Investigation, Formal analysis, Methodology, Visualization, Validation, Writing - original draft. **Tudor Mocanu:** Software, Investigation, Writing - original draft. **Thomas Pregger:** Software, Formal analysis, Resources. **Markus Quante:** Conceptualization, Supervision, Resources, Writing - review & editing. **Martin Ramacher:** Software, Investigation, Visualization. **Stefan Seum:** Project administration, Resources, Funding acquisition, Writing - original draft, Writing - review & editing. **Christian Winkler:** Methodology, Software, Resources, Supervision.

Acknowledgement:

Funding for the project “Transport Development and the Environment” was provided by the Helmholtz Association under its Transport Research Program in the research field of Aeronautics, Space and Transport. Funds stem from the Federal Ministry for Economic Affairs and Energy (BMW). Ten Institutes of the German Aerospace Center (DLR), the Karlsruhe Institute of Technology and the Helmholtz-Zentrum Geesthacht participated in the project.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trd.2020.102536>.

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